

FINAL TECHNICAL REPORT

PRELIMINARY REPORT ON THE LATE HOLOCENE SLIP RATE ALONG THE CENTRAL CALAVERAS FAULT, SOUTHERN SAN FRANCISCO BAY AREA, GILROY, CALIFORNIA

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Program Elements: I and II

U.S. Geological Survey
National Earthquake Hazards Reduction Program
Award Number 00-HQ-GR-0073

December 16, 2002

Research supported by U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 00-HQ-GR-0073. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

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ABSTRACT

Preliminary Report on Late Holocene Slip Rate Along the Central Calaveras Fault, Southern San Francisco Bay Area, Gilroy, California

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This paleoseismic study of the central Calaveras fault provides information that revises earlier estimates of the late Holocene slip rate for the fault. Our investigation at the San Ysidro Creek site consisted of geologic mapping, excavation, and documentation of six trenches across and parallel to the fault, and deposit age-estimation through radiocarbon analyses. The objectives of the study are to evaluate the age and amount of displacement of buried paleochannels that cross the main active strand of the central Calaveras fault, and thus, to estimate a late Holocene geologic slip rate. The trench exposures provide evidence of cumulative dextral offset of at least six paleochannels, and possibly as many as eight paleochannels. The four oldest paleochannel deposits range in age from about 4.1 ka to 2.5 ka.¹

Stratigraphic and structural relations suggest that the four oldest and relatively well-constrained paleochannels provide a geologic slip rate that ranges from 8 to 19 mm/yr for the central Calaveras fault. This slip rate encompasses the entire amount of uncertainty in the slip rate estimate and from the measured channel offsets and the deposit ages. This slip rate is similar to our initial estimated slip rate developed during our earlier study at the site (Kelson et al., 1998). The current slip rate estimate reflects better constraints on the maximum and minimum locations of upstream paleochannels intersecting the fault. The pending results of 26 detrital charcoal samples collected from the newly identified paleochannels located east and west of the fault will provide improved constraints and reduced uncertainty on the late Holocene slip rate for the central Calaveras fault.¹

¹ We are awaiting the analyses of 26 detrital charcoal samples at the U.S. Geological Survey's funded radiocarbon dating program at Lawrence Livermore National Laboratory, which should provide age information on the younger offset paleochannel deposits. Because these data are critical to the assessment of the fault slip rate, the results presented herein are considered preliminary.

1.0 INTRODUCTION

Probabilistic evaluations of seismic hazards require well-constrained data on the behavior of faults over geologic time periods, including data on the timing of past earthquakes, the long-term rate of fault movement, and the amount of slip generated by large fault ruptures. From these data, information can be developed on the likelihood of large earthquakes within a given future time period (e.g., Working Group on California Earthquake Probabilities [WGCEP], 1999), which, in turn, provide input to the mitigation of seismic hazard for critical and non-critical engineered facilities. Even in seismically active regions, the historical record of earthquakes commonly is inadequate for providing fault behavioral data, and paleoseismologic studies are needed to obtain data on fault slip rate, earthquake timing, and amounts of coseismic rupture. This study is targeted at obtaining these types of data on the central segment of the Calaveras fault in the southern San Francisco Bay region, northern California (Figure 1).

Regional seismic hazards in the southern San Francisco Bay region are dominated by the San Andreas and Calaveras faults, which accommodate the majority of relative motion between the North American and Pacific plates at a latitude of about 37°N (Figure 1) (Kelson et al., 1992a). However, there is a lack of paleoseismic data on the central Calaveras fault where it traverses the eastern margin of the heavily populated and industrialized Santa Clara Valley. Because of the recent rapid population growth and the likelihood of continued urban expansion into the southern Santa Clara Valley, this fault poses a significant seismic hazard to a growing population and industrial complex. Key unknowns concerning the fault include: whether or not the fault can produce large (>6 M) earthquakes, late Holocene slip rate, timing of large past earthquakes, and amount of coseismic rupture.

The primary purpose of our investigation at the San Ysidro Creek site is to evaluate the late Holocene slip rate along the central Calaveras fault, through analysis of the amount of offset and estimated age of paleochannel deposits that cross the fault. To achieve this goal, we investigated a site east of the town of Gilroy (Figure 1), where the fault is characterized by prominent geomorphic expression and offset fluvial deposits at the mouth of a small drainage, San Ysidro Creek (Figure 2). The study involved detailed documentation of paleoseismologic trenches, and age-dating analyses of faulted deposits completed during an initial phase (Kelson et al, 1998) and a second phase (presented herein). We develop a preliminary late Holocene (4 ka) slip rate based on offset paleochannels, and await results of radiocarbon analyses of younger offset paleochannels to evaluate the fault slip rate over the past 2,000 years.

The San Ysidro Creek site contains numerous buried paleochannels of San Ysidro Creek that cross the fault and are displaced northwest from a 10-m-wide gorge cut into bedrock on the east side of the fault. During our previous study, we excavated three fault-normal trenches (trenches T-1, T-4 and T-5) that define the location of the 1-m-wide primary fault strand (Figure 2). In addition, we excavated two fault-parallel trenches (trenches T-2 and T-3) southwest of the fault, which exposed four southeast-trending late Holocene paleochannels incised into claystone of the Plio-Pleistocene Santa Clara Formation. These channels intersect the fault between 35 to 50 m northwest of the bedrock gorge, and provide useful piercing lines for assessing cumulative middle to late Holocene slip on the fault.

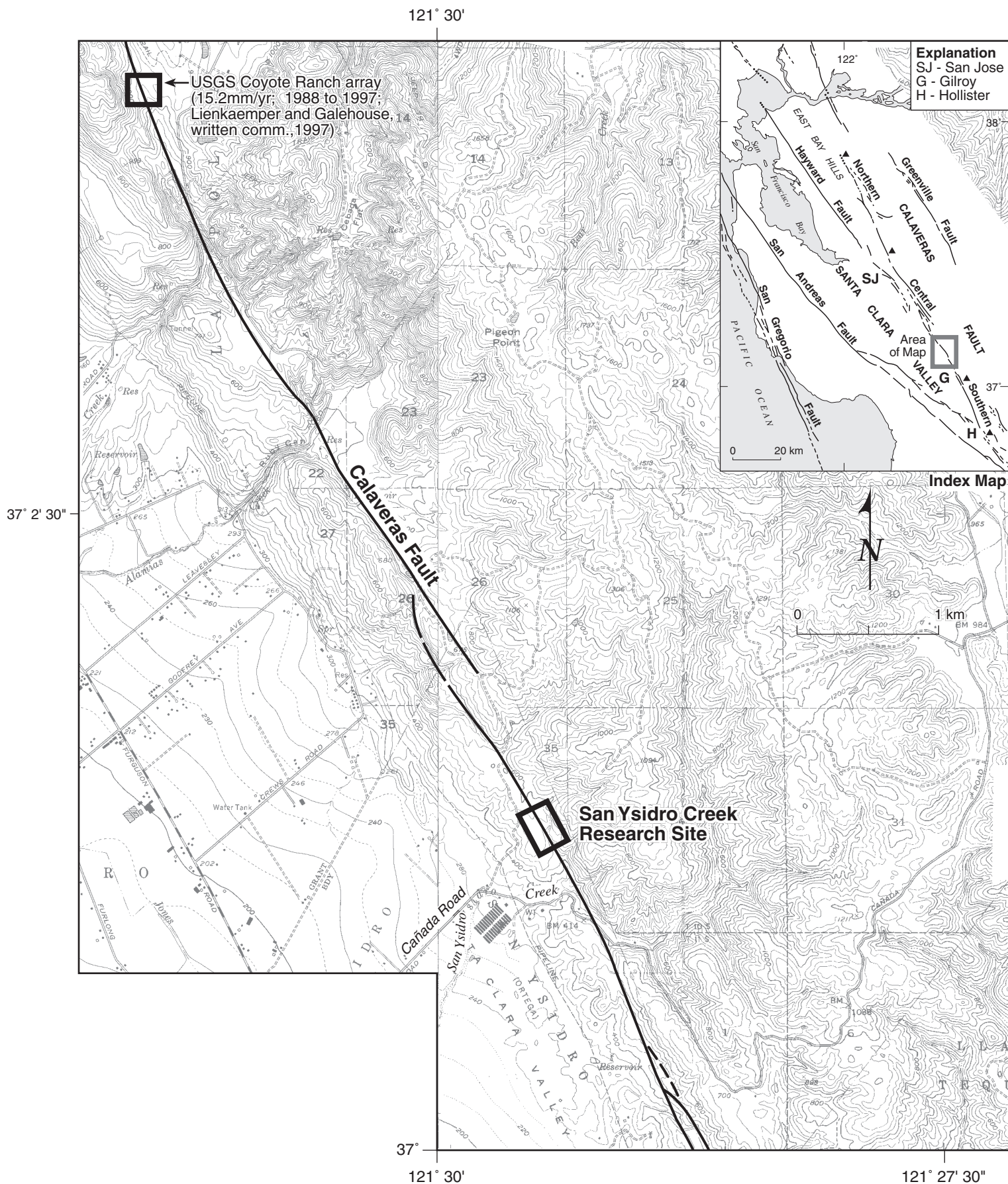


Figure 1. Topographic map of part of the central Calaveras fault, showing the location of the USGS creep measurement site, and the San Ysidro Creek site. Base maps: Gilroy and Gilroy Hot Springs 7-1/2 minute quadrangles.

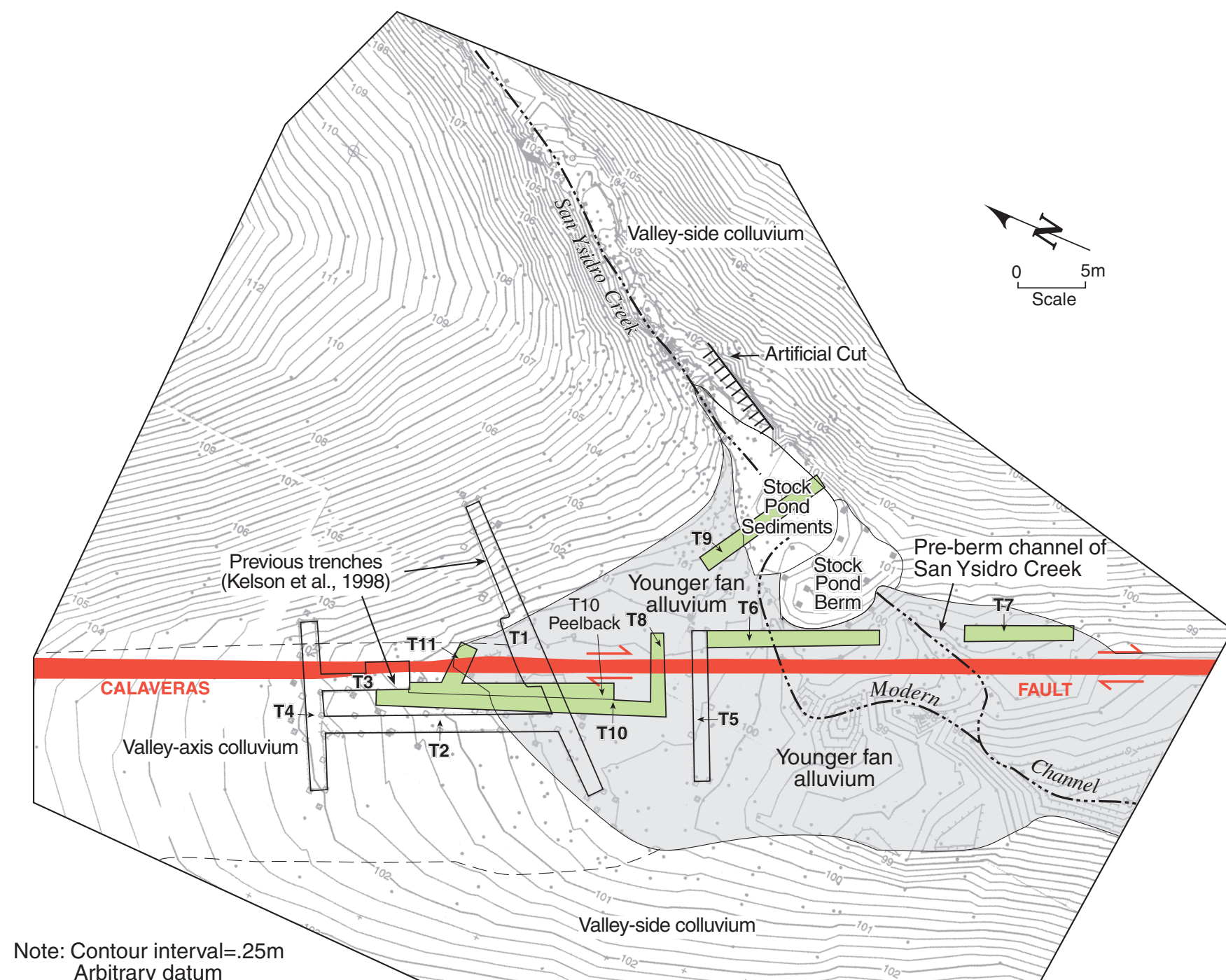


Figure 2. Surficial geologic map of San Ysidro Creek site, showing the Calaveras fault, locations of previous trenches (T1 through T5), and trenches T6 through T11 from this study.

This study also is designed to better constrain the initial slip rate estimates of previously documented offset paleochannel deposits (PC-1 to PC-4) and to assess younger offset paleochannels for the purpose of obtaining a late Holocene slip rate. Uncertainty in the location of the paleochannels on the northeast side of the fault is the greatest source of uncertainty in estimating the slip rate (e.g., greater than uncertainty in the ages of the paleochannels). Therefore, we excavated fault-parallel trenches (trenches T-7 and T-9) on the northeastern side of the fault to define the locations of the paleochannels upstream of the fault (Figure 2), and to provide additional age constraints for the offset paleochannels. We also excavated a fault-parallel trench (trench T-10 and T-10 peel-back) on the southwestern side of the fault to expose, if present, younger paleochannels, and thus to hopefully provide a post-2.5 ka slip rate.

2.0 GEOLOGIC AND SEISMOLOGIC SETTING

The 146-km-long Calaveras fault traverses the eastern margin of the southern Santa Clara Valley (Figure 1), where it is a major structural boundary between the San Francisco Bay structural depression and the Diablo Range (Page, 1982; Mooney and Luetgert, 1982; Brankman and Hitchcock, 2002). The fault has had a long history of deformation, with strike-slip faulting beginning about 3.6 Ma, and a total dextral offset of 16 to 24 km. We interpret that the presently active Calaveras fault consists of three major sections that are defined by contemporary seismicity, structural relations with other major faults, rate of present-day creep, and geomorphic expression. These sections, which may or may not reflect actual earthquake rupture segments, are the (Figure 1):

- Northern Calaveras fault (NCF, from the town of Danville to Calaveras Reservoir),
- Central Calaveras fault (CCF, from Calaveras Reservoir to San Felipe Lake), and
- Southern Calaveras fault (SCF, from San Felipe Lake to the Paicines fault, south of Hollister).

The active Calaveras fault clearly plays a major role in the distribution of dextral slip within the San Andreas fault system in the San Francisco Bay area. South of the Bay area, the San Andreas fault has a long-term slip rate of about 34 mm/yr (Sieh and Jahns, 1984; Sims, 1991), which partitions onto several faults north of about latitude 36.5°N. Near the town of Hollister, approximately 12 to 17 mm/yr of slip partitions from the San Andreas fault onto the 24-km-long SCF, leaving about 17 to 22 mm/yr on the San Andreas, San Gregorio, and other faults in the southern Santa Cruz Mountains.

At a latitude of about 37°N (near the town of Gilroy), the 70-km-long CCF has an historic creep rate of about 15 mm/yr between 1988 and 1997 (J. Galehouse [SFSU] and J. Lienkaemper [USGS], written comm., 1997), which is consistent with a geologic slip rate of 15 to 20 mm/yr estimated by Perkins and Sims (1988) and Sims (1991) for the SCF. Farther northwest, east of the city of San Jose (Figure 1), slip on the CCF then partitions onto the southern Hayward fault (8 to 10 mm/yr, Lienkaemper et al., 1991) and the NCF (4 to 7 mm/yr, Kelson et al., 1992a, b, 1996; Simpson et al., 1999). Slip on the NCF, in turn, may be transferred westward back onto

the Hayward fault via distributed deformation within the East Bay hills (Aydin and Page, 1984; Kelson et al., 1993, 1995, Kelson and Simpson 1998; Unruh and Lettis, 1997).

The CCF exhibits abundant microseismicity (Bakun, 1980, 1984; Reasenber and Ellsworth, 1982; Bakun and Lindh, 1985; Oppenheimer et al., 1990; Du and Aydin, 1992) and has generated several recent moderate-magnitude earthquakes (i.e., 1949 Gilroy M_W 5.2, 1979 Coyote Lake M_W 5.9, 1984 Morgan Hill M_W 6.2, 1988 Alum Rock M_W 5.1, and 1998 Gilroy M_W 4.0). Oppenheimer et al. (1990) note that the CCF consists of six “segments” (referred to herein as “subsections”), two of which are interpreted as most likely to generate a moderate-magnitude earthquake in the near future. The Working Group on Northern California Earthquake Potential (WGNCEP, 1996) estimated that the most likely maximum magnitude earthquake along the SCF and CCF is M_W 6.2, based on the historical earthquake history and an interpretation that there is little or no present-day strain accumulating along the fault. Contemporary seismicity along the SCF and CCF led Oppenheimer and Lindh (1992) to estimate a 33% probability of a M_6 earthquake on the fault in the next 30 years. However, Oppenheimer et al. (1990) could not preclude the possibility of a larger earthquake on the fault.

This research focuses on the 70-km-long CCF, which, prior to this study, had little or no available information on paleoseismic fault behavior. The San Ysidro Creek study site lies east of the town of Gilroy (Figure 1), within the epicentral area of the 1949 M_W 5.2 earthquake and within one of the subsections noted by Oppenheimer et al. (1990) as likely to produce a moderate-magnitude earthquake. However, there are no geologic data addressing whether this subsection (and adjacent subsections) could rupture in large earthquakes. In addition, although this subsection of the CCF exhibits evidence of about 15 mm/yr of surface creep, there are no geologic data on long-term slip rate or paleoearthquake timing. This research is designed to obtain data that will better characterize the paleoseismic behavior of the CCF, and provide input to estimates of time-dependent probabilities of large earthquakes in the San Francisco Bay area.

3.0 RESULTS

3.1 Site Geomorphology and Near-Surface Stratigraphy

The San Ysidro Creek site lies along the main, well-expressed strand of the CCF, as mapped by Dibblee (1973a, b), Radbruch-Hall (1974), Smith (1981) and Witter and Kelson (in press). Fault-related geomorphic features along this strand in the site vicinity include topographic scarps, offset rills, closed depressions, linear drainages, and springs and seeps that are indicative of active surface deformation. At the site, the fault trace is marked by a linear, northwest-trending hill front that is crossed nearly orthogonally by San Ysidro Creek (Figure 2). Directly upstream of the fault, San Ysidro Creek flows in a narrow southwest-trending, 15-m-deep bedrock valley that is inset into Plio-Pleistocene sandstone, siltstone, and claystone of the Santa Clara Formation. Further upstream, the creek is inset into Cretaceous siltstone, sandstone and conglomerate bedrock. The alluviated valley of San Ysidro Creek contains fluvial sediments derived from the Cretaceous bedrock and Santa Clara Formation, and colluvial deposits shed from northwest-trending linear ridges bordering the site. These alluvial and colluvial sediments have been translated northwestward along the fault, and are preserved northwest of and at the mouth of San Ysidro Creek (Figure 2).

Our earlier studies performed at this site included the excavation and documentation of five trenches (T-1 to T-5) oriented parallel and normal to the central Calaveras fault to: (1) yield a preliminary geologic slip rate and (2) speculate on the presence or absence of coseismic surface-fault rupture from large magnitude earthquakes (Kelson et al., 1997; Kelson et al., 1998). As part of our 2nd-year supplemental investigation, we excavated six additional trenches (trenches T-6 to T-11) at the San Ysidro Creek site to assess near-surface stratigraphy, and style of faulting, for the purpose of characterizing right-laterally offset paleochannel deposits. Based on trench exposures, the alluvial sediments deposited by San Ysidro Creek unconformably overlie semi-consolidated, Pliocene and Pleistocene bedrock of the Santa Clara Formation (Figure 3). This bedrock ranges from greenish-brown claystone and siltstone to reddish-brown sandy and clayey bedded gravel. The pervasively sheared claystone and siltstone contains abundant calcite-rich veins, dips moderately northwest and is distinct from the overlying Holocene fine- to coarse-grained alluvium and colluvium. Where Santa Clara Formation bedrock consists of bedded gravel, as in trench T-6, it is more difficult to differentiate this material from Holocene alluvium deposited by San Ysidro Creek. We, therefore, use the presence of: (1) a reddish hue, (2) large rounded clasts, (3) clay films present in matrix and along the base of clasts, (4) north-dipping bedding, and (5) calcium carbonate development, as diagnostic criteria indicating the presence of Santa Clara Formation. In trenches T-1, T-4, T-8 and T-11, the Santa Clara Formation is in fault contact with late Pleistocene to early (?) Holocene landslide deposits, as well as fine-grained colluvium and alluvium. Below, the Holocene stratigraphy encountered in trenches east and west of the fault zone is described.

3.1.1 Stratigraphy Southwest of the Central Calaveras fault

Holocene alluvial deposits preserved on the southwest side of the fault include channel-fill and alluvial fan deposits derived from San Ysidro Creek, as well as colluvium within and bordering the linear fault valley. The channel-fill deposits are the stratigraphically lowest Holocene surficial deposits, and are overlain by recent alluvial fan deposits near the mouth of San Ysidro Creek (trenches T-5 and T-8), and by colluvium farther to the northwest. Trenches T-1, T-3, T-4, T-10 and a peel-back along the northeastern wall of trench T-10, show the presence of at least four and possibly up to eight separate channel-fill deposits that are inset either into Santa Clara Formation or Holocene alluvium and colluvium (Figure 4 and 5). On the west side of the fault, from northeast to southwest, we designate the channel-fill deposits as Paleochannel One to Paleochannel Eight (Figure 4 and 5). In general, the channel-fill deposits consist of poorly sorted sandy gravel, with subrounded pebbles to boulders of sandstone, siltstone, and basalt. The gravel is derived from Plio-Pleistocene and Cretaceous rocks located in the headwaters of San Ysidro Creek. Finer-grained paleochannel deposits locally are bedded with fine and medium gravel, and occasional sand lenses, whereas the coarser paleochannel deposits are characterized by poor sorting and poor bedding, and clast imbrication. Close to the fault, as exposed in trenches T-3 and T-10, the channel thalwegs are inset into Santa Clara Formation, and indicate a spacing of about 2 to 4 m with width increasing down valley (Figures 4 and 5). The presence or absence of bedding truncations, degree of sorting, bedding, color, clay films, and manganese staining of the paleochannel deposits provide relatively moderate diagnostic indicators for differentiating between the numerous paleochannel deposits, and evidence that the paleochannels progressively decrease in age to the southeast (Figures 4 and 5). We further differentiate the paleochannel deposits using subtle textural changes in lithology, variable paleoflow directions, and

Trench T1 – South Wall

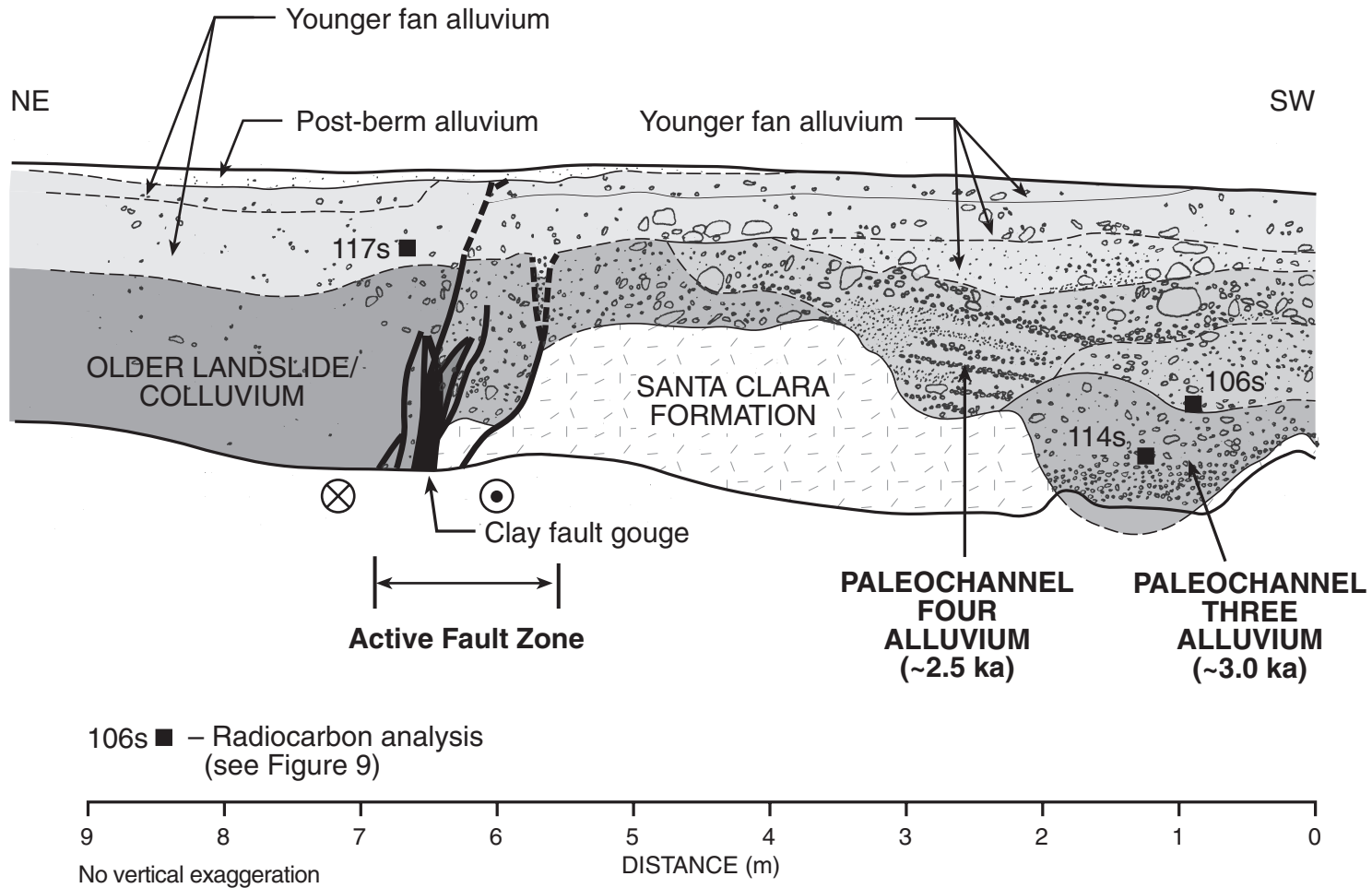


Figure 3. Simplified log of the southern wall of trench T1, San Ysidro Creek site, showing active strand of central Calaveras fault, displaced and undisplaced geologic units, and locations of analyzed radiocarbon samples (from Kelson et al., 1998).

Trench T3

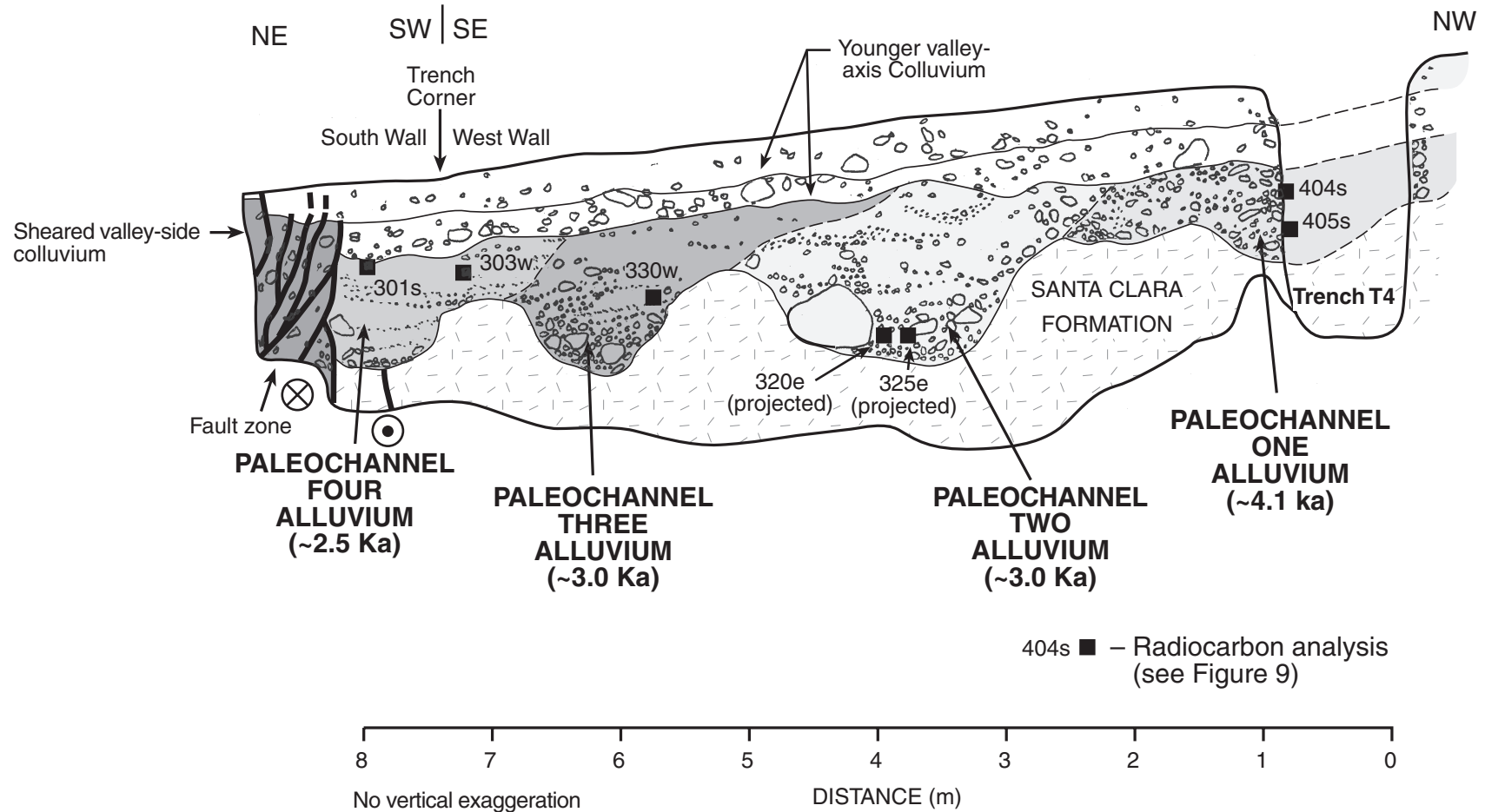


Figure 4. Simplified log of the western and southern walls of trench T3, San Ysidro Creek site, showing active strand of Calaveras fault, displaced geologic units, and locations of analyzed radiocarbon samples (from Kelson et al., 1998).

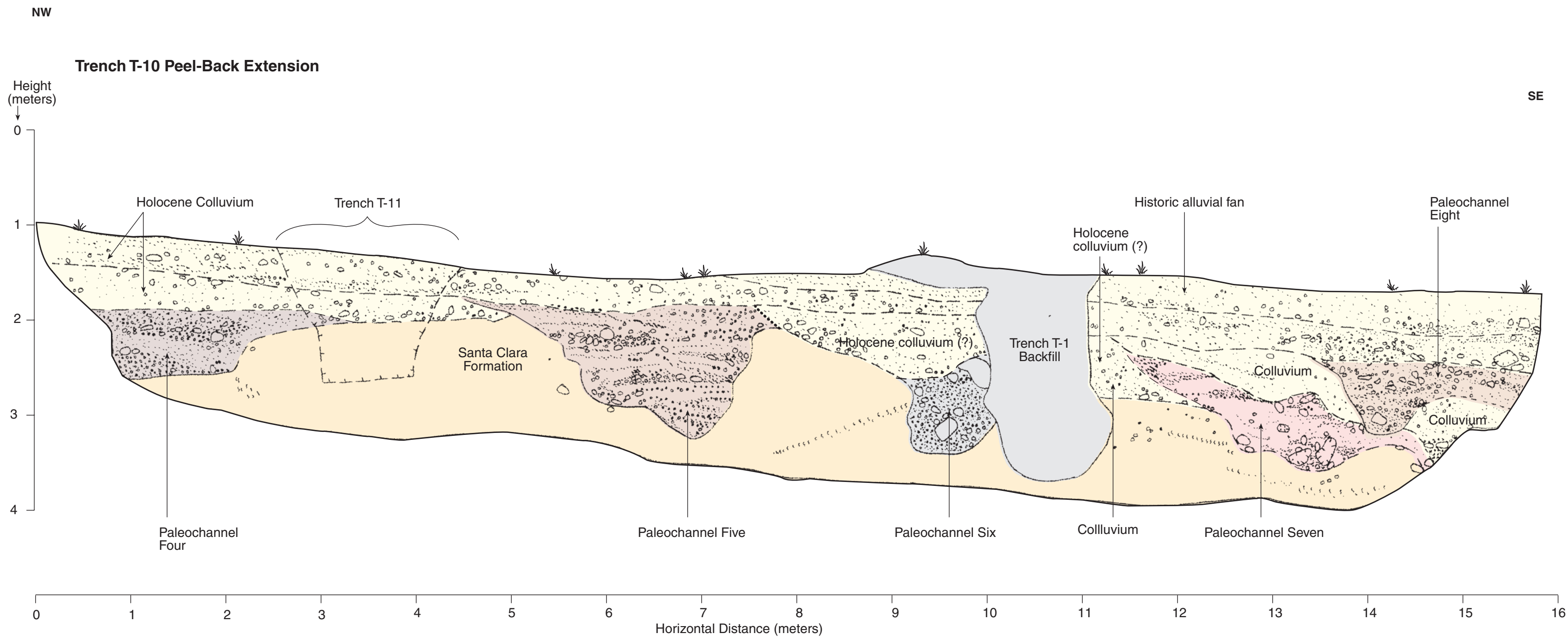


Figure 5. Simplified log of the eastern wall of Trench T-10 peel-back showing San Ysidro Creek paleochannels displaced along the central Calaveras fault.

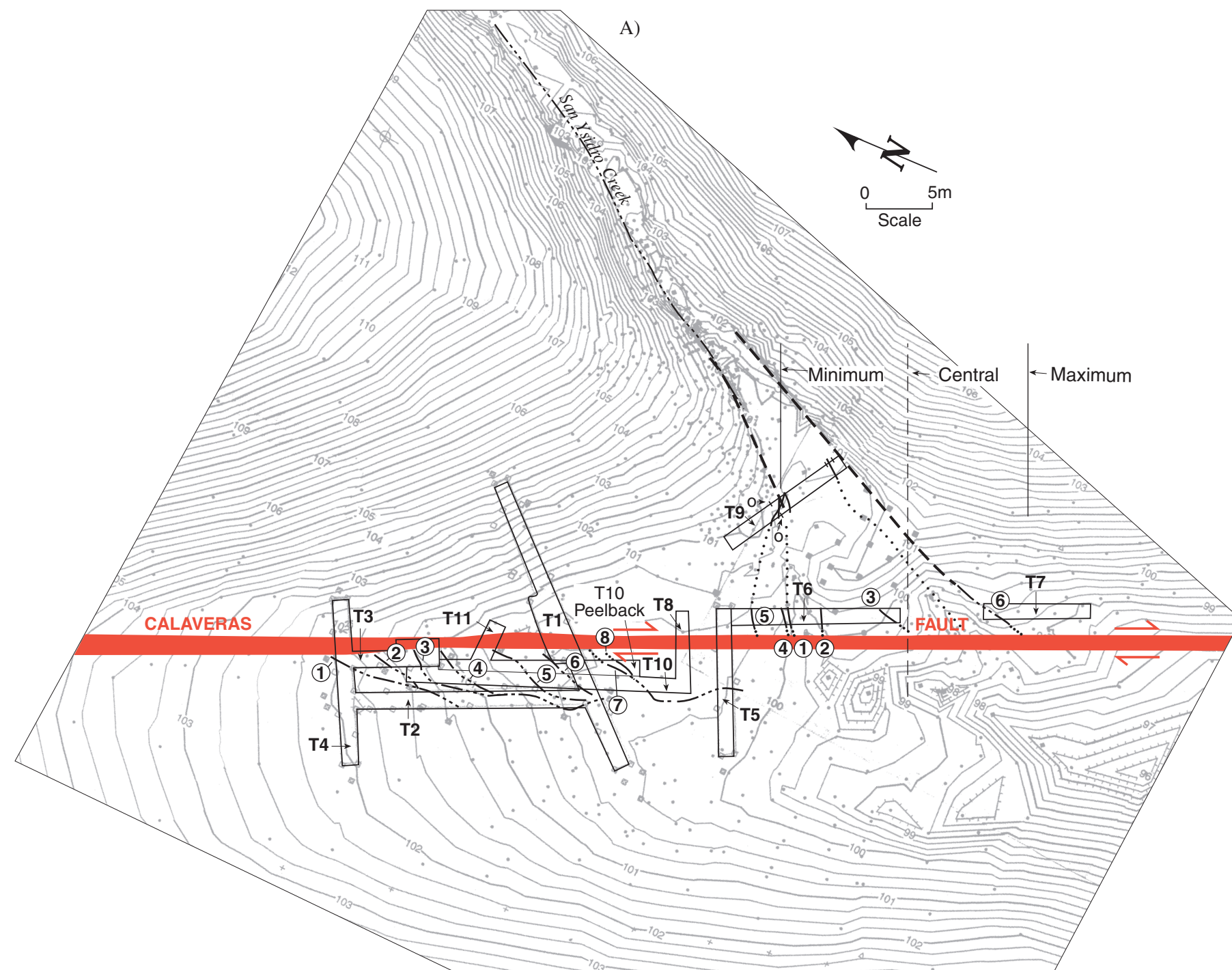
stratigraphic position at or near the fault zone. Using these sedimentological and structural characteristics, paleochannels generally can be correlated between trenches T-2 to T-4, and T-10. Similar diagnostic criteria are used to differentiate between paleochannel deposits east of the fault. However, because of the significant distance between trenches T-6 and T-10 and the possibility that correlative fluvial deposits in trench T-6 were scoured away (see below), correlation of these paleochannel deposits across the fault is problematic. Also, in the southeastern part of trench T-10, the paleochannels are difficult to distinguish because the younger channel-fill deposits coalesce with other paleochannel deposits. Paleoflow indicators (e.g., channel margins and thalwegs measured across the trench) show that in the southeastern part of trench T-10, the paleochannels flowed to the southeast in essentially the same stream valley leaving only isolated remnants of older channel deposits (Figure 6).

The paleochannel deposits west of the fault are overlain by poorly bedded, poorly sorted colluvium, with minor discontinuous bedded overland-flow deposits. The colluvium is derived from the northwestern part of the linear valley, and contains subangular to subrounded pebbles and cobbles of primarily sandstone and siltstone. The colluvium truncates the uppermost beds of the paleochannel deposits. Overlying the colluvium between trenches T-1 and T-5 is a bedded fine to coarse gravel with sand interbeds derived from a historic flood. These historic flood deposits appear to be associated with the construction of a stock pond across San Ysidro Creek (Figure 2).

3.1.2 Stratigraphy Northeast of the Central Calaveras Fault

Stratigraphy exposed northeast of the fault in trenches T-1, and T-4 to T-9, indicates that there is a change in depositional style between trenches T-5 and T-8. For instance San Ysidro Creek channel deposits are absent northeast of trench T-5. Northwest of trench T-5 and east of the fault, the deposits exposed in the trenches generally consist of colluvium and landslide deposits as well as Santa Clara Formation (Figure 3). The colluvium and landslide deposits grade into and/or are faulted against the coarse colluvium west of the fault that is derived from uplifted San Ysidro Creek paleochannel material translated northwest along the fault. Historic flood deposits consisting of bedded sand and gravel overlie colluvium and landslide deposits between trenches T-1 and T-6.

East of the fault, trenches T-5 to T-7, and T-9 show a complex depositional history, including alluvial fan progradation, channel-fill deposition and degradation. Exposures in trench T-5 and the northwestern part of trench T-6 indicate that poorly sorted, massive alluvial fan deposits unconformably overlie bedded clayey gravel of the Plio-Pleistocene Santa Clara Formation (Figure 7). In trench T-5, the alluvial fan deposits are truncated at the fault against Holocene paleochannel deposits and Santa Clara Formation southwest of the fault (Kelson et al., 1997, 1998). The alluvial fan deposits consist of poorly sorted, massive, gravelly sandy clay and clayey sand that are truncated to the southeast in trench T-6 by bedded and coarse-grained paleochannel deposits derived from San Ysidro Creek. The presence of a buried soil horizon near the base of the alluvial fan package provides evidence that there was a brief period of landscape stability following the deposition of the lowermost alluvial package. This buried soil post-dates the oldest paleochannel exposed directly east of the fault (Figure 7). The buried soil horizon is observed in



B)

Western Paleochannel	Offset in meters		
	Minimum	Central	Maximum
One	35	43	52
Two	32	40	49
Three	28	38	46
Four	27	35	44
Five	22.5	32	40
Six	19	28	37
Seven	15	24	32.5
Eight	14	23	31

Figure 6. Detailed map of the San Ysidro Creek site, showing trench locations and paleochannels offset by the central Calaveras fault. Paleochannel designations are not necessarily correlative across the fault.

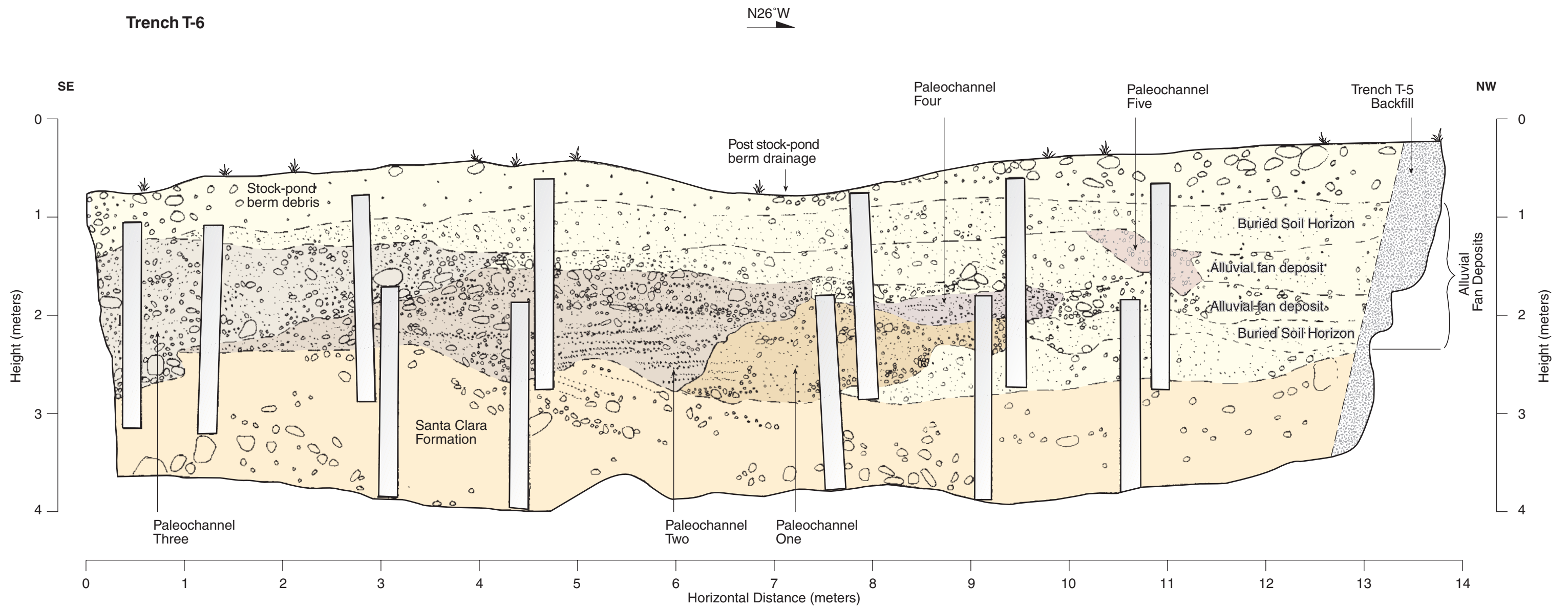


Figure 7. Simplified log of the western wall of Trench T-6, San Ysidro Creek site, showing locations of paleochannel deposits directly east of the fault.

trenches T-5, T-6 and T-8 and appears to represent the former ground surface prior to the incision and deposition of Paleochannel One, located east of the fault (Figures 5 and 6). Note paleochannel designation east and west of the fault are not necessarily correlative. We are awaiting the results of submitted detrital charcoal samples for radiocarbon analyses to provide further evidence for correlation of similar deposits across the fault and between trenches.¹

A second, younger buried soil horizon developed in the alluvial fan package is present directly below the base of the stock pond debris. This buried soil documents the former ground surface prior to the stock-pond placement (Figure 7). This soil is nearly laterally continuous across trench T-6 and is present in trenches northwest of trench T-5 indicating that prior to the construction of the stock pond, San Ysidro Creek flowed across the fault in the area southwest of trench T-6. The younger buried soil is not present in trench T-7 (Figure 8). In trench T-7, recent(?) or very young flood deposits bury a prominent soil developed in Holocene colluvium. This soil is better developed than either of the buried soils encountered in trench T-6 indicating some stability along the eastern banks of San Ysidro Creek.

At least six paleochannel deposits are exposed east of the fault. These paleochannel deposits each have one moderately well-constrained channel margin (e.g., typically the northern margin only) (Figure 7). The channel-fill deposits consist of poorly- to well-bedded sand and clayey gravel that unconformably overlie bedded gravel of the Santa Clara Formation. The southeastern extent of the channel-fill deposits is documented by exposures in trench T-7, which show bedded fluvial gravel and sand inset into Santa Clara Formation and overlain by Holocene overbank fines and colluvium (Figure 8).

Trench T-9 excavated at the mouth of San Ysidro Creek exposed several distinct channel-fill deposits inset into reddish-brown gravelly claystone of the Santa Clara Formation. Paleoflow directions based on thalweg and channel margins projected across trench T-9 show west to southwest-trending flow directions (Figure 6). Notably, bedrock is present throughout trench T-9 at depths of less than 1 m below the ground surface, and appears to step down to the west about 2 to 3 meters southwest of trench T-9 based on exposures in a dewatering ditch cut between trenches T-6 and T-9. The drainage ditch exposed recent stock pond deposits of bedded silt, clay and fine-grained sand with gravel overlying paleochannel deposits that pre-date the construction of the stock pond. The uppermost part of these young alluvial-fan deposits contain historic artifacts and appear to be related to the breaching of a small stock-pond berm that used to extend across the San Ysidro Creek channel. Following the breaching of this berm, San Ysidro Creek flowed west of the berm near trenches T-5 and T-6 (Figure 2). Recent incision along the present-day active channel appears to be migrating upstream across the fault trace and into historic sediments that were deposited behind the stock-pond berm.

¹ We are awaiting the analyses of 26 detrital charcoal samples at the U.S. Geological Survey's funded radiocarbon dating program at Lawrence Livermore National Laboratory, which should provide age information on the younger offset paleochannel deposits. Because these data are critical to the assessment of the fault slip rate, the results presented herein are considered preliminary.

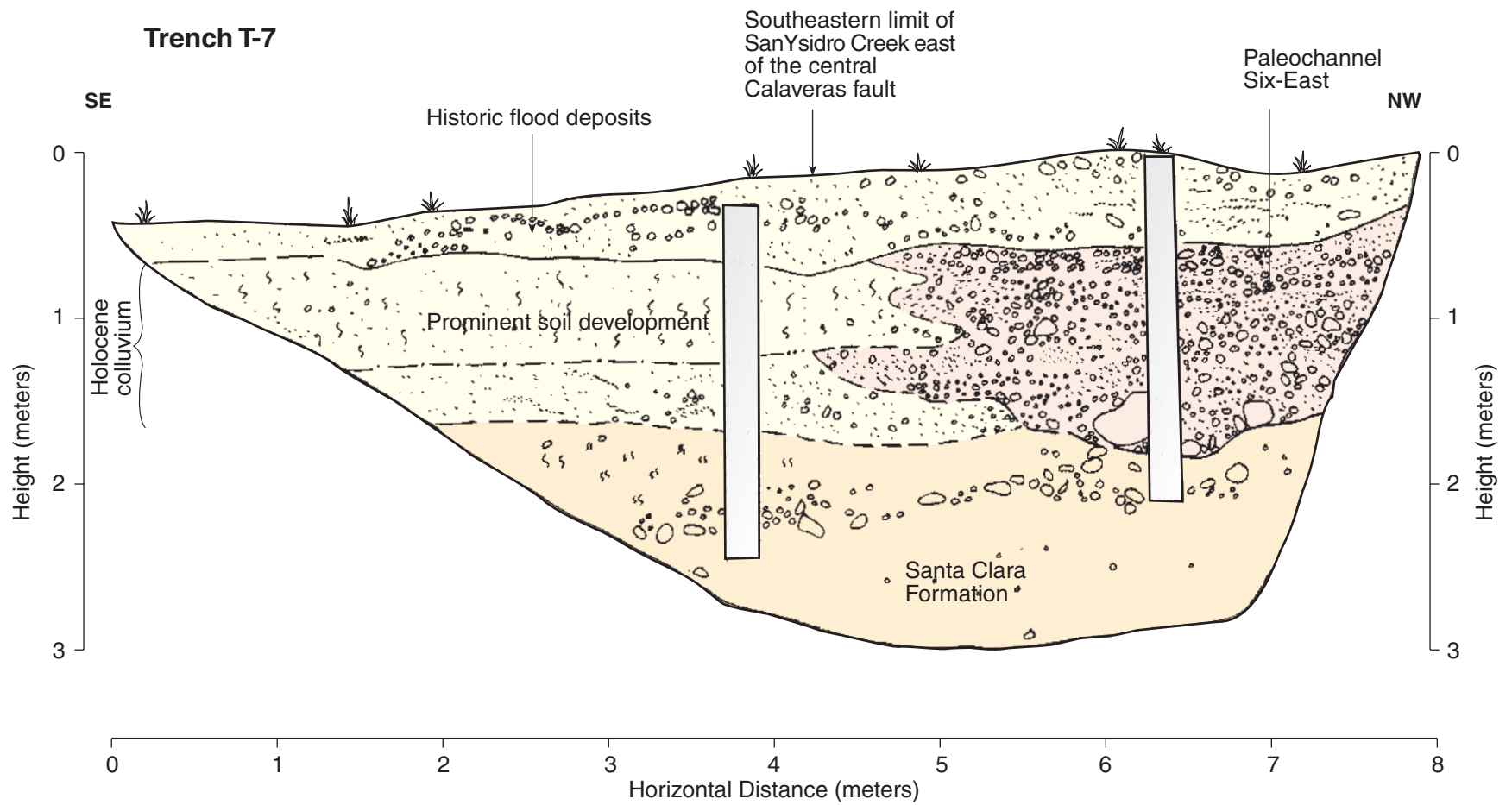


Figure 8. Simplified log of the western wall of Trench T-7, San Ysidro Creek site, showing paleochannel deposits east of the fault and the southeastern limit of incision by San Ysidro Creek.

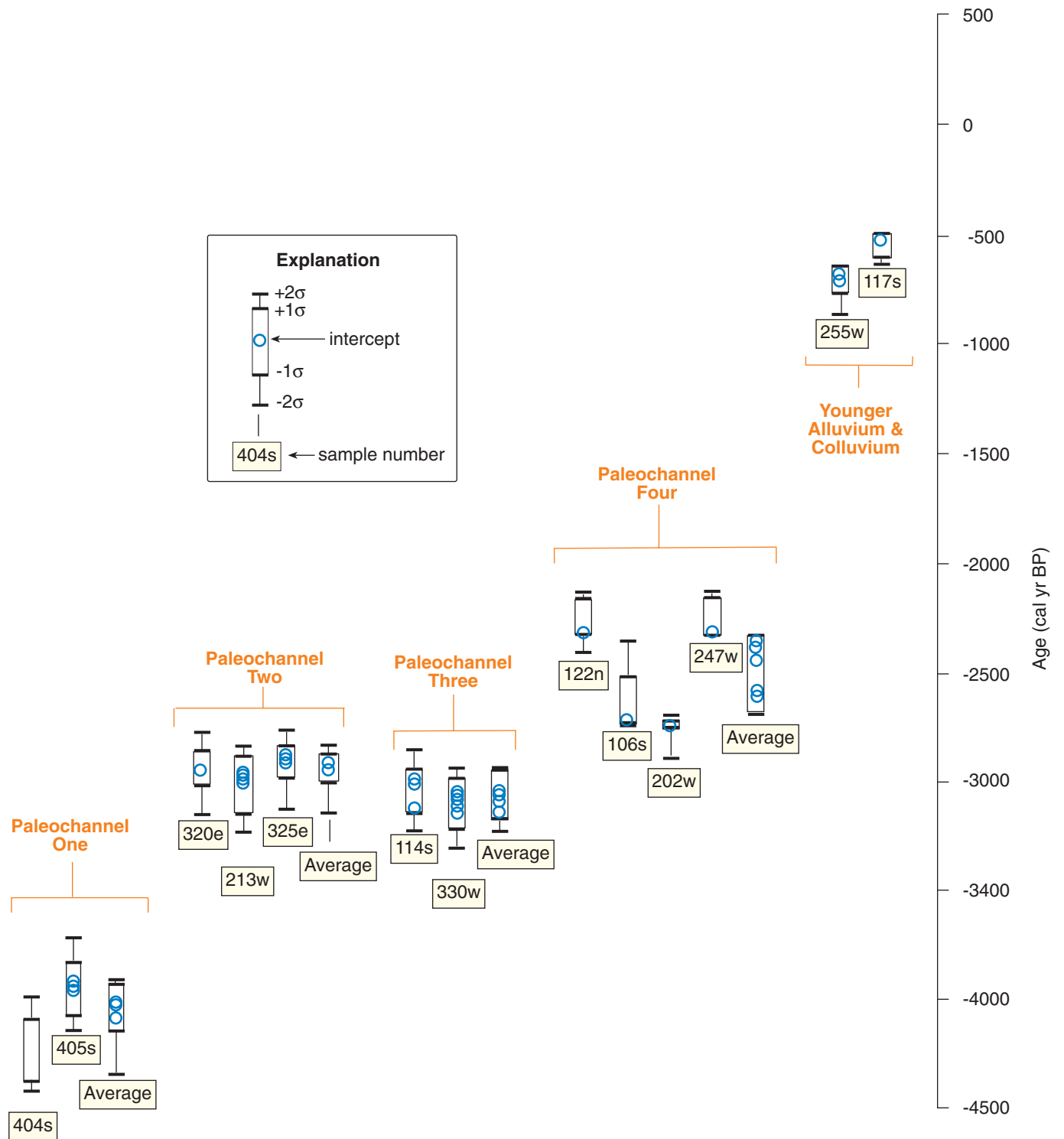


Figure 9. Summary of radiocarbon analyses, San Ysidro Creek site.

3.1.3 Age of Deposits

Age-estimates of the surficial deposits at the San Ysidro Creek site are based on cross-cutting stratigraphic relationships and sixteen radiocarbon analyses on charcoal fragments collected from the surficial deposits (Kelson et al., 1998) (Figure 9). Because radiocarbon results are pending for our 2nd-year of study, at the time of writing this report we use data from our previous trenching to estimate deposit ages. Overall, the previous radiocarbon analyses for Paleochannels One through Four provide a suite of stratigraphically consistent age-estimates, although three analyses are inconsistent (Figure 1). Two samples from Paleochannel One (samples 404s and 405s, Figure 1) yielded an average calibrated date of 4340 to 3910 cal. yr BP (Figure 9, based on 2 standard deviations). On this basis, we estimate an age for Paleochannel One of 4.1 ± 0.2 ka. Three samples from Paleochannel Two (samples 320e, 213w, and 325e, Figure 1) yielded an average calibrated date of 3160 to 2850 cal. yr BP, from which we estimate an age of 3.0 ± 0.2 ka (Figure 9). The average date for Paleochannel Two is statistically different from the date for Paleochannel One at the 95% level of confidence.

Two samples from Paleochannel Three (samples 114s and 330w, Figure 9) yielded an average calibrated date of 3240 to 2950 cal. yr BP. This age range overlaps the age range from the stratigraphically older Paleochannel Two, and the two ranges are statistically indistinguishable at the 95% level of confidence. Although the stratigraphic cross-cutting relationships show that Paleochannel Three is younger than Paleochannel Two, the radiocarbon analyses support a similar age, within uncertainties. Thus, we interpret an age of 3.0 ± 0.2 ka for Paleochannel Three (Figure 9).

Paleochannel Four yielded six samples with sufficient carbon to be analyzed (samples 106s, 122n, 202w, 237e, 301s, and 303w, Figure 9). However, two of these samples yielded dates that are anomalously old (samples 301s and 303w). We interpret these samples to be older, reworked detrital charcoal, and do not use these dates in further analyses. The four remaining samples from trenches T1 and T2 yielded an average calibrated date of 2720 to 2360 cal. yr BP, from which we interpret an age of 2.5 ± 0.2 ka for Paleochannel Four (Figure 9). The average date for Paleochannel Four is statistically different from the average date for Paleochannel Three at the 95% level of confidence.

Two samples from colluvium and alluvium overlying the paleochannel deposits provide minimum-limiting age estimates for the paleochannels. Sample 255w was collected from colluvium above the four channels, and yielded a calibrated date of 880 to 660 cal. yr BP (Figure 9). Sample 117s, in turn, was collected from a younger alluvium inset into the colluvium and the four channel deposits. This sample yielded an average calibrated date of 650 to 510 cal. yr BP (Figure 9). Both of these dates support a latest Holocene age for the younger alluvium adjacent to the present-day San Ysidro Creek channel.

In summary, the trenches at the San Ysidro Creek site show the presence of six and up to possibly eight discrete paleochannels cut into bedrock on the western side of the Calaveras fault. These paleochannels are overlain by southeasterly dipping, coarse colluvium, which in turn is overlain by southwesterly dipping younger alluvium inset into the colluvium. The four oldest distinct channels (PC-1 to PC-4) range in age from about 4.1 ka to 2.5 ka, whereas the colluvium and younger alluvium are about 700 to 600 years old. We are awaiting ages for the younger

paleochannel deposits encountered during our 2nd-year of study at the site.

3.2 Near-Surface Structural Relations

The location of the main active strand of the central Calaveras fault is constrained at the San Ysidro Creek site on the basis of exposures in five fault-normal trenches (T-1, T-4, T-5, T-8 and T-11) and in the eastern wall of fault-parallel trench T-3 (Figure 2). These exposures show a linear fault trace that is aligned with a linear hill front both northwest and southeast of San Ysidro Creek (Figure 2). In all of the trench exposures, the main fault strand is near-vertical, locally having dips of 75° or greater to either the northeast or southwest (e.g., Figure 3), although in the northwestern wall of trench T-4, the fault zone broadens upward and includes a prominent strand that dips moderately to the east. Some of the strands within the fault zone are associated with gouge that is as much as 25 cm wide (Figure 3). The trench exposures show that fault strands displace surficial deposits in a zone that is less than 2 m wide. Shearing within the underlying Santa Clara Formation is extensive and occurs in a zone that is more than 5 m wide. Fault kinematic indicators were well preserved as continuous slickensides in fault gouge in the eastern wall of trench T-3. The slickensides have a trend of N25°W to N30°W and a plunge up to 15°SE, suggesting predominantly right-lateral offset with a minor component of east-down vertical separation at the trench site. The sense of vertical separation suggested by the slickensides (i.e., southwest side up) is consistent with the presence of Santa Clara Formation in the fault-normal trench exposures on the western side of the fault, but absent east of the fault in trenches T-1, T-3, T-4, T-8, and T-11.

In trenches T-1, T-3, T-4 and T-11, the fault zone forms the contact between older (late Pleistocene to early Holocene?) landslide deposits on the east and younger (late Holocene) alluvium and colluvium on the west. In trenches T-3, T-4 and T-8, fault strands or distinct fractures extend upward nearly to the ground surface, deforming all deposits except the very uppermost 1 to 2 cm of material affected by active colluviation and/or biological (bovine) activity. In trench T-8, the fault extends to within 20 cm of the surface based on distinct fractures and offset of the historical bedded flood deposits associated with breaching of the stock pond. In these historical deposits the fault is associated with fracturing of the loose gravel, indicating that the fault at the site is undergoing aseismic creep. Also, in trench T-8, the 1-m-wide fault zone is defined by two prominent fault traces that truncate Holocene alluvial fan deposits and colluvium on the east against Santa Clara Formation and Holocene fluvial deposits on the west. Deposits present east of the eastern fault trace are warped down to the west 0.6 m providing evidence for a southwest side up vertical separation across the fault zone. Similar to the fault exposures present northwest of trench T-8, the presence of truncated Pliocene and Pleistocene Santa Clara Formation west of the fault suggests an overall west-side up apparent vertical separation across the fault zone.

3.2.1 Paleochannel Offsets

This study builds upon our previous research on the central Calaveras fault at San Ysidro Creek, which documented the right-lateral offset of four distinct late Holocene paleochannels, designated Paleochannel One through Paleochannel Four (Kelson et al., 1998). Interpretation of stratigraphic, geomorphic and age relations of these four paleochannels provided initial data on the late Holocene slip rate on the central Calaveras fault (Kelson et al., 1997, 1998). The

individual paleochannel thalwegs were shown to intersect the fault between 34 to 51 m northwest of the bedrock gorge, and thus provided piercing points that yielded a preliminary cumulative fault offset and slip rate(s). However, the greatest source of uncertainty with these earlier slip rate(s) was estimating the location of the corresponding paleochannels east of the fault, and the northern and southern boundary of San Ysidro Creek as it approaches the fault zone. Therefore, the intention of this study is to reduce the uncertainty in the geologic slip rate determined from our previous work at the site by exposing late Holocene paleochannels east of the fault. To accomplish this task, we excavated several trenches southwest and northeast of the fault, as well as across the fault. The following sections describe our basis for correlating the paleochannels east and west of the fault.

Paleochannels West of the Fault

Trenches T-1 through T-5 identified Paleochannels One through Four (from northeast to southwest) that flowed to the south-southwest across the fault (Figure 6). The eastern projection of these thalwegs into the fault zone are well constrained, because the eastern wall and floor of trench T-3 exposed the main strand of the Calaveras fault and the western wall exposed the four paleochannels. As shown on Figure 6, the intersections of Paleochannels One through Four and the fault are located at or directly adjacent to the eastern wall of trench T-3. The amount of uncertainty in the location of all four thalweg piercing points directly west of the fault is less than 1 m (the width of the trench). The uncertainty in the piercing point location west of the fault is higher in the area southeast of trench T-3. For instance, in trench T-4, the paleochannel deposits become more difficult to differentiate because the channel-fill deposits interfinger and coalesce with a common southeast-trending zone (Figure 6).

To expose potential paleochannel deposits southeast of trench T-3, we excavated trench T-10 and a 1-m-wide peel-back of the eastern wall of trench T-10 (Figure 6). These excavations exposed as many as two and up to possibly four additional paleochannels that are incised into the Santa Clara Formation and Holocene fluvial deposits. We designate these additional paleochannels as Paleochannel Five to Paleochannel Eight (from northeast to southwest, respectively) and are differentiated from other paleochannels based on cross-cutting stratigraphic relationships, lithology, presence or absence of bedding, and clay film development (as described above).

The eastern wall of trench T-10 provided clear exposures of narrow, distinct bedrock-cut channels in the northwestern half of the trench, whereas the southeastern part of the trench the channel morphology and cross-cutting relationships are less clear. This is because the channels broaden and begin to intersect Holocene fluvial and colluvial deposits. The 1-m-wide peel of trench T-10 provided further constraints on the location and orientation of the paleochannels exposed in the northwest part of trench T-10 as they approach the fault, as well as rectifying unclear stratigraphic relationships present in the southeastern end of trench T-10 (Figure 5).

The peel-back of trench T-10 approached to within 1 m of the fault zone and exposed buried paleochannel deposits prior to intersecting the fault zone. The thalwegs and channel dimensions are well to moderately constrained between trench T-10 and the peel-back, and show that the paleochannels flowed southwest directly west of the fault (Figure 6). After crossing the fault, the paleochannel flow directions appear to become more subparallel to the fault zone as they

encounter older alluvial deposits (Figure 6). Paleochannels Five to Seven are incised into claystone bedrock directly west of the fault. We interpret a Paleochannel Eight that is incised into Paleochannel Seven and Holocene colluvium. Based on cross-cutting relationships, the paleochannels become sequentially younger to the southeast. The stratigraphic relationships also suggest that the younger paleochannel deposits (i.e., Paleochannel Seven and Eight) crossing the fault encounter a thick sequence of fluvial material deposited within the linear alluvial paleovalley as it is transported northwesterly across the apex of San Ysidro Creek. In addition, the trenches demonstrate that the depth to the Santa Clara Formation increases from the northwest to the southeast, further demonstrating that the older deposits located in the northern part of the site (near trench T-4) have experienced a greater amount of cumulative vertical uplift than the paleochannel deposits exposed in trenches T-5, T-6 and T-8 (Figure 2).

Paleochannels East of the Fault

On the upstream (eastern) side of the fault, the alluvial stratigraphy is far more complex and consists of bedded alluvial fan deposits and inset channel-fills that are inset into Holocene alluvium and bedded clayey gravel of the Santa Clara Formation. Directly northeast of the fault, trench T-6 exposed at least three and possibly as many as five channel-fills, designated from oldest to youngest as Paleochannel One to Paleochannel Five (Figure 6). Paleochannels One to Paleochannel Three are inset into Santa Clara Formation. These three paleochannel deposits resemble the channel-fill deposits observed west of the fault in that they are high-energy deposits consisting of bedded sand and gravel; however, they lack the distinct bedrock notches associated with the paleochannel deposits present west of the fault. In addition, cross-cutting relationships suggest that the paleochannels decrease in age in a southeast direction as noted by the progression of younger paleochannels inset into older paleochannel deposits (Figure 7). Paleochannels Four and Five are narrow, 1-to 1.5-m wide channels that consist of loose sandy gravel with little or no clayey matrix. Based on the absence of a clayey matrix, and an absence of reddening of the deposits, we interpret these two channel-fills as relatively young deposits. Orientations derived from the northern channel margins and interpreted thalwegs of Paleochannels One to Paleochannel Three provide flow direction estimates of about S40°W and S73°W, or slightly more westerly than the orientations of other thalwegs present west of the fault (Figure 7). Paleochannels Four and Five are close to the N40°W orientation of Paleochannels One and Two. The southeastern limit of incision by the paleo-San Ysidro Creek is preserved in trench T-7, which exposes a grayish-brown, loose, well bedded channel-fill (Paleochannel Six) inset into Santa Clara Formation and is conformably overlain by Holocene colluvium and overbank material. Paleochannel Six trends more southerly across the fault zone than the paleochannels exposed in trench T-6.

Estimated Cumulative Right-lateral Displacement

On the basis of exposures of trenches T-6 and T-7, coupled with the absence of paleochannel deposits east of the fault zone in trenches T-5 and T-8, we estimate that the northern limit of incision by distinct paleochannels east of the fault is constrained within trench T-6 near Paleochannels One and Four. The southeastern limit of the fluvial valley is constrained in trench T-7 by Paleochannel Six (Figure 6). The northern and southern extent of the buried paleochannel thalwegs are limited by these constraints. Therefore these limits of the former paleovalley provide minimum and maximum amounts of lateral offset of piercing points (buried paleochannel thalwegs) west of the fault (Figure 6). Using these constraints, we estimate

cumulative right-lateral offsets of between 14 and 52 m for the eight paleochannel thalwegs west of the Calaveras fault (Figure 6). Because the channel thalwegs are well constrained west of the fault, and moderately to well constrained east of the fault based on exposures in trenches T-6 and T-7, we estimate that each of these offsets have a measurement uncertainty of about ± 1 m.

Notably, the trench exposures east of the fault show that several of the paleochannels are nearly orthogonal to the Calaveras fault at the site. Downstream of the fault the channels have a southerly orientation and are more oblique at an angle of about 20 to 35° between the fault and the channels (Figure 6). These oblique orientations of the paleochannels west of the fault show that the former creek quickly occupied the southeast trending valley after crossing the fault.

4.0 DISCUSSION

4.1 Late Holocene Slip Rate Estimate

The absence of age control data for Paleochannels Five through Eight make it difficult to estimate the late Holocene slip rate derived from these younger paleochannels. Therefore, we use the new subsurface information collected east of the fault to better constrain the cumulative offset of Paleochannels One through Four. The ages and amounts of offsets of Paleochannels One through Four west of the fault, as well as distribution of Paleochannels One through Six east of the fault, provide a means to evaluate the slip rate of the Central Calaveras fault. The ranges in slip rate are based on the previously estimated ages of Paleochannels One through Four west of the fault, and their associated right-lateral displacement are based on the revised maximum and minimum constraints east of the fault (Figure 6). The ranges in slip rate based on the estimated ages of each paleochannel and the cumulative offset of the paleochannel deposits are shown on Figure 10, with “central” values reflecting our best estimate of paleochannel age and a central projection of San Ysidro Creek toward the fault. The preferred values of the slip rates range from 10.5 to 14.0 mm/yr, and the full range of slip rates, including known uncertainties, is from 8.1 to 19.1 mm/yr (Figure 10). Assuming that the mean of the mean is a valid statistical parameter for this population, an average late Holocene geologic slip rate for the CCF of about 11 to 14 mm/yr, or 12 (+ 2, -1) mm/yr, can be estimated. At this point, however, we prefer encompassing the entire amount of uncertainty in our slip rate estimate, and thus suggest a late Holocene slip rate estimate of 14 +5, -6 mm/yr. The level of uncertainty in the slip rate estimate is based on the uncertainty in the age of the paleochannel deposits, and the relatively large uncertainty regarding the location of the specific paleochannels east of the fault. It is possible that the pending radiocarbon results for samples collected east of the fault zone can refine this uncertainty by identifying probable paleochannel matches east of the fault.

The differences between the cumulative offsets estimated in our previous study and the results from this study are related to revised interpretations of the maximum and minimum locations of the paleochannels east of the fault. Trench T-6 demonstrates that the former course of San Ysidro Creek may have flowed more westerly than previously interpreted. In addition, trench T-7 shows that the southeastern limits of the San Ysidro Creek paleochannels are more southwesterly than previously hypothesized based on the geometry of the bedrock canyon.

Offset (m)			
Paleochannel	Minimum	Central	Maximum
One	35	43	52
Two	32	40	49
Three	28	38	46
Four	27	35	44

Age (ka)			
Paleochannel	Minimum	Central	Maximum
One	3.9	4.1	4.3
Two	2.8	3.0	3.2
Three	2.8	3.0	3.2
Four	2.3	2.5	2.7

Slip Rate (mm/yr)			
Paleochannel	Minimum	Central	Maximum
One	8.1	10.5	13.3
Two	10	13.3	17.5
Three	8.8	12.7	16.4
Four	10	14.0	19.1

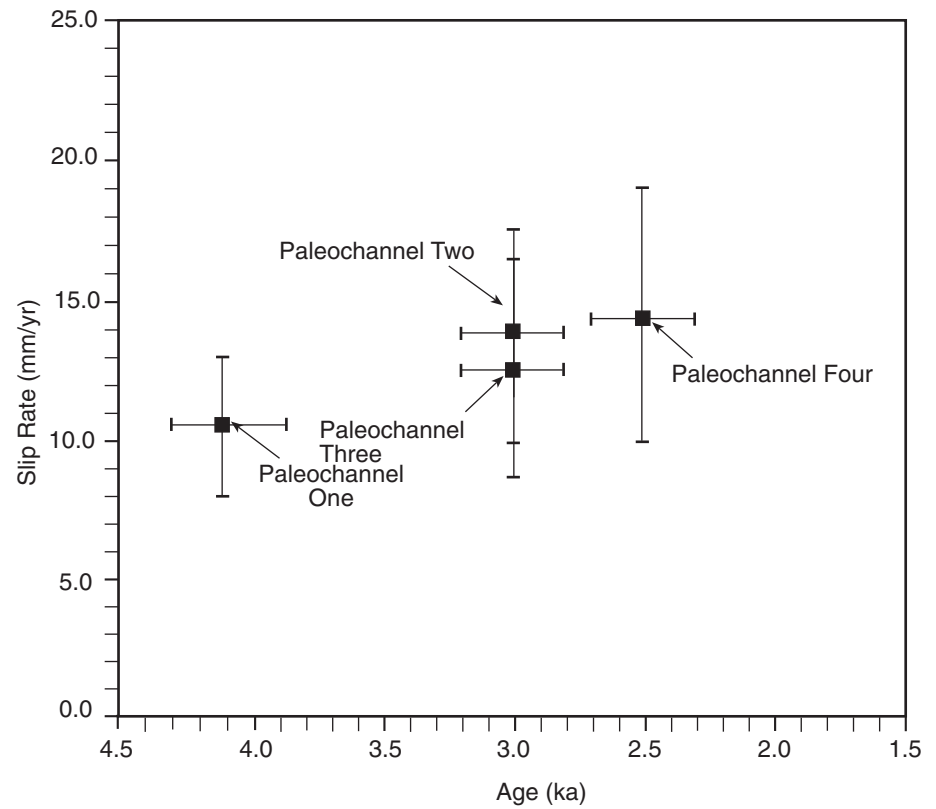


Figure 10. Summary of offsets and ages of Paleochannels One to Four, and estimated slip rates, San Ysidro Creek site.

The age and offset of Paleochannel One suggests a post-4.1 ka rate of 8 to 13 mm/yr (Figure 7). Paleochannels Two and Three yield post-3.0 ka rates of between 10 and 17.5 mm/yr, and Paleochannel Four yields a post-2.5 ka rate of about 10 to 19 mm/yr. Although uncertainties are too large to make definitive conclusions, these data suggest a possible increase in the time-averaged slip rate for younger piercing lines. Figure 10 shows that the central values of the four slip rate estimates increase for progressively younger piercing lines.

5.0 SUMMARY

This study provides a revised estimate of the middle to late Holocene slip rate of the central Calaveras fault at San Ysidro Creek. The site is along the central section of the fault, which is characterized by a high creep rate (~15 mm/yr), abundant historical seismicity, and prominent geomorphic expression of right-lateral movement. Through excavation of six trenches across and parallel to the fault, we identify possibly up to four additional displaced paleochannels (Paleochannels Five through Eight) that provide the opportunity to further evaluate the late Holocene slip rate along the fault. Our previous study that identified Four paleochannel deposits west of the fault, whose locations are herein refined to provide new constraints on the maximum and minimum amount of cumulative right-lateral displacement across the fault. The trenches exposed a single, narrow fault zone traversing the site. Paleochannels One through Four have dextral offsets from an incised bedrock valley that range from 27 to 52 m. The ages of the paleochannels are based on multiple radiocarbon analyses, and range from 4.1 to 2.5 ka. Overall, the time-averaged late Holocene slip rate is encompassed by a range of 14 ± 5 , -6 mm/yr.

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